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# **Chug and Buzz .... The Neglected and Disrespected Combustion Instabilities**

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# What is Combustion Instability ?



Embed movie



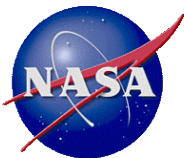
# “Low” Frequency versus “High” Frequency

- “High” frequency combustion instability gets all the press
  - “Screech”
  - Can be very harmful when it happens
  - But does not really happen that often any more
  - Associated with the acoustic modes of the combustion chamber
- “Low” frequency combustion instability gets no press
  - “Chug”
  - Yet it happens on almost every program and during almost every start and shutdown transient
  - Can be more harmful than you realize
- Sometimes the two types meet in the middle
  - “Buzz”
    - “intermediate” frequency combustion instability
  - Two types have been observed
    - One combining injector organ pipe modes and chamber transverse modes
    - One combining injector Helmholtz modes and chamber longitudinal modes
  - Has been happening quite often lately



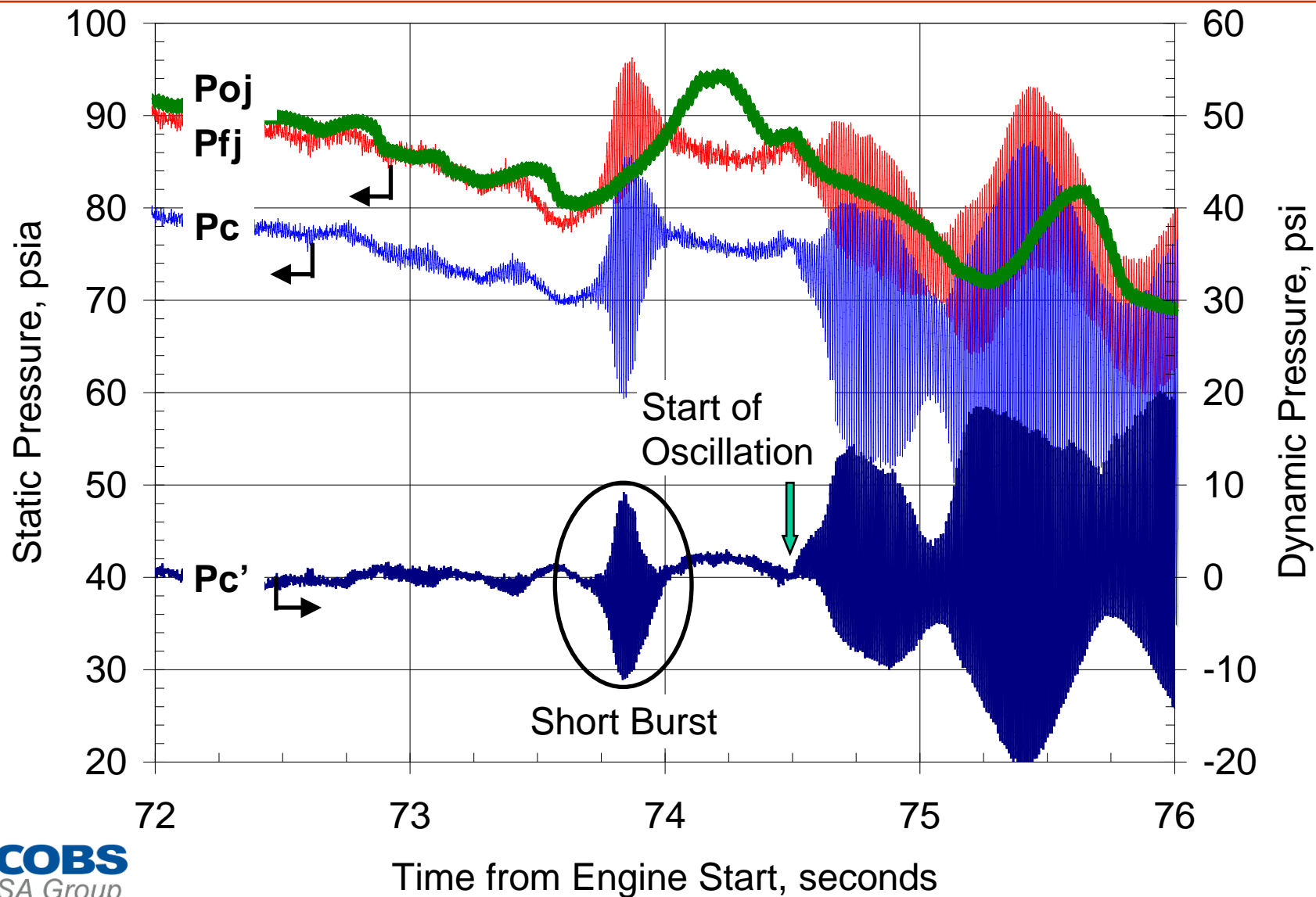
# Chug

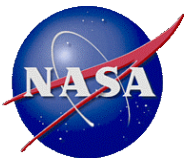
- Bulk oscillations of the combustion chamber gas
  - No spatial pressure variations in the combustion chamber
  - Pressure wave shapes are *usually* sinusoidal
  - One or both injector manifolds are engaged
- Happens on almost every engine
- You may think there is nothing new here...
  - Predictable, easy to analyze ??
    - Analytical methodology improvements still being made
    - Most methods still rely on calculation of a “timelag”
      - If you estimate incorrectly, chug occurs unexpectedly
  - Happens ? So what ?
    - Things break...
      - Instrumentation, fittings & connections, ceramic parts
    - Performance decreases
      - oscillating mixture ratio and reduced efficiency of injection processes
    - Undesired structural vibrations
    - Trouble with ignition



# "Nice" Chug

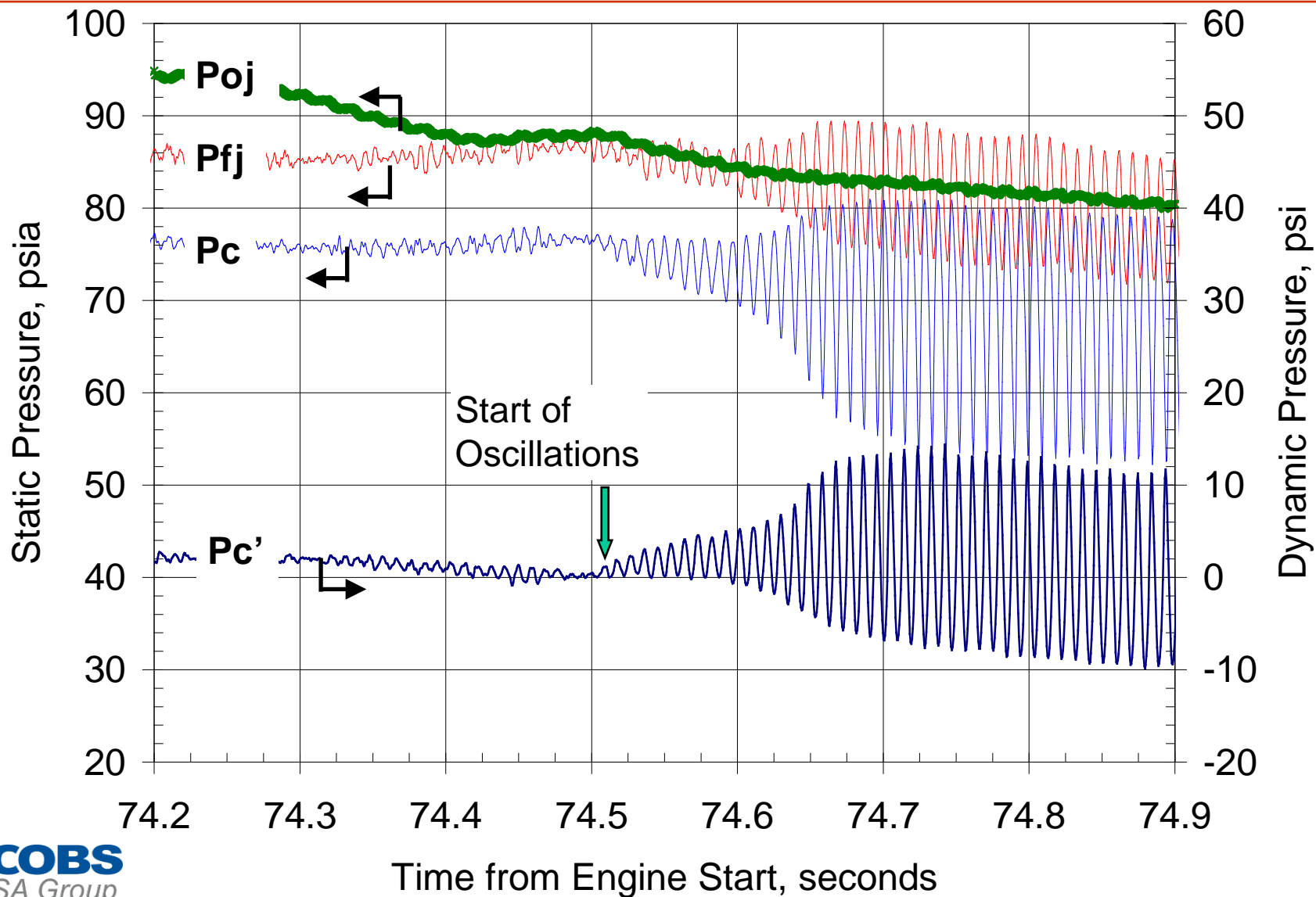
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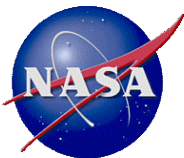




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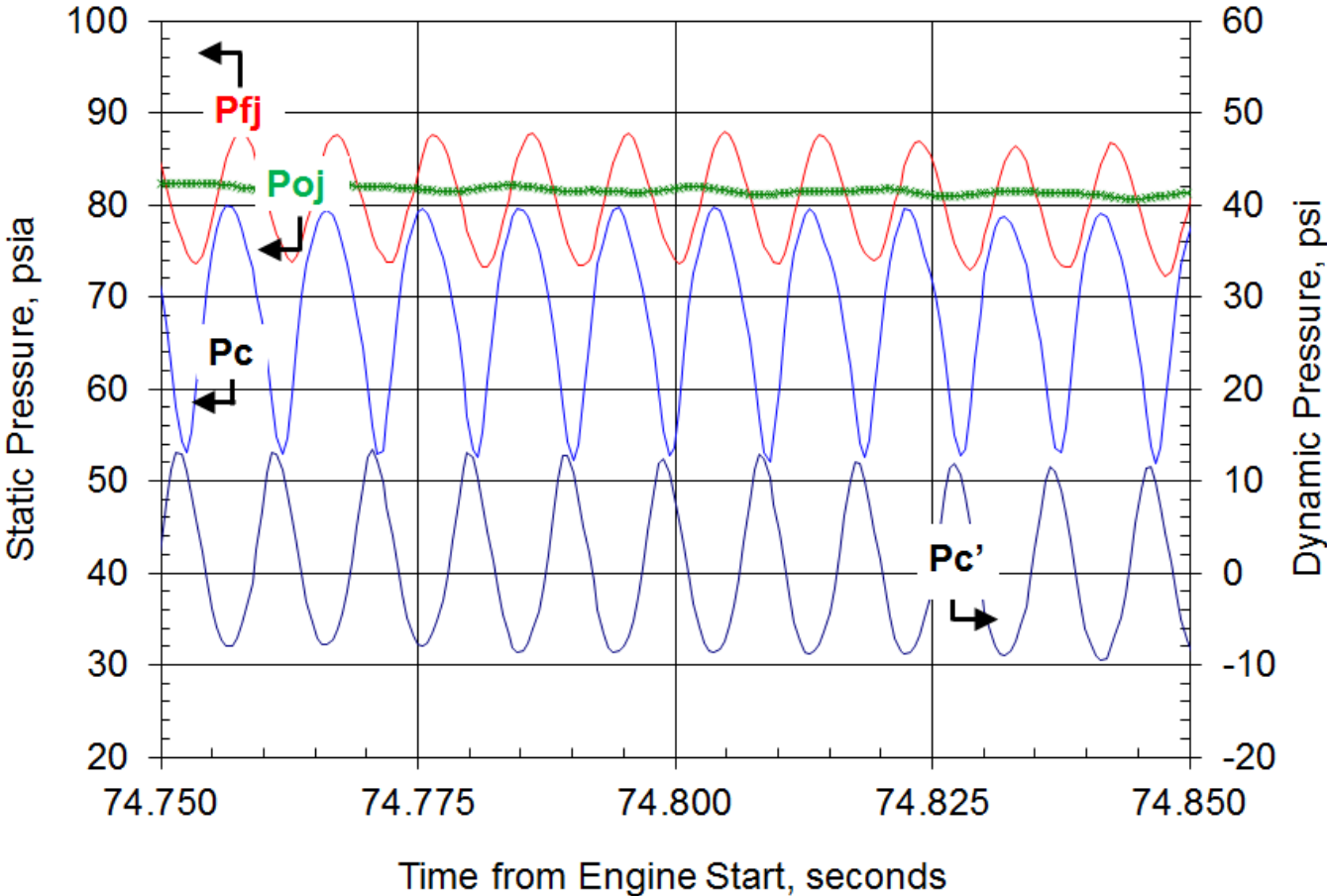
## “Nice” Chug (Closeup)

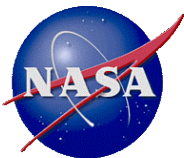




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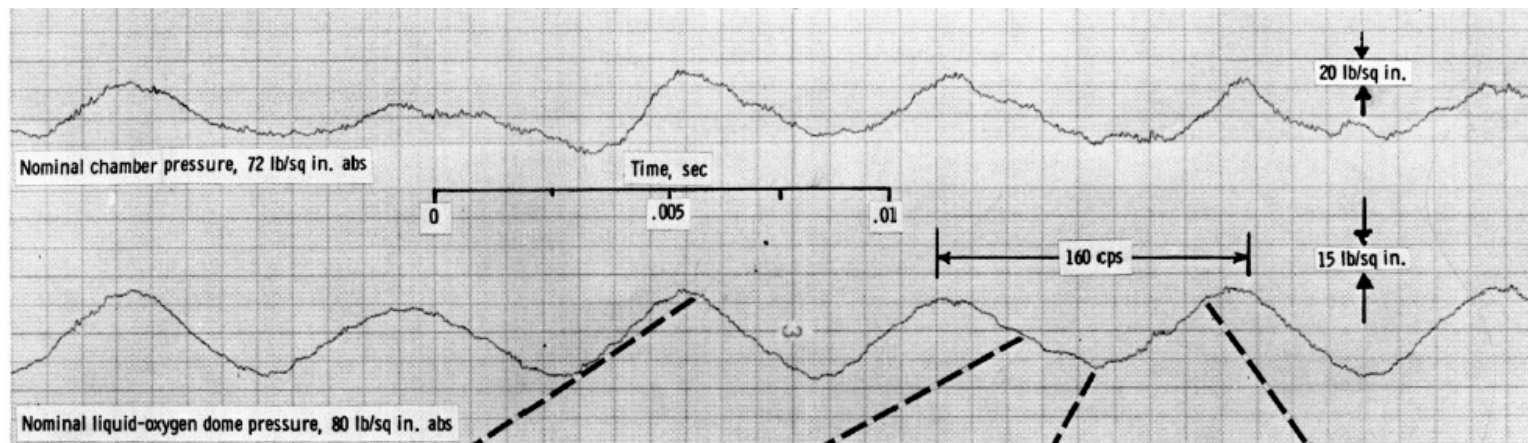
# “Nice” Chug (Closeup)





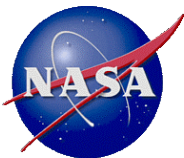
# Appearance of Vapor in LOX Manifold During 1964 RL-10 Chugging Tests

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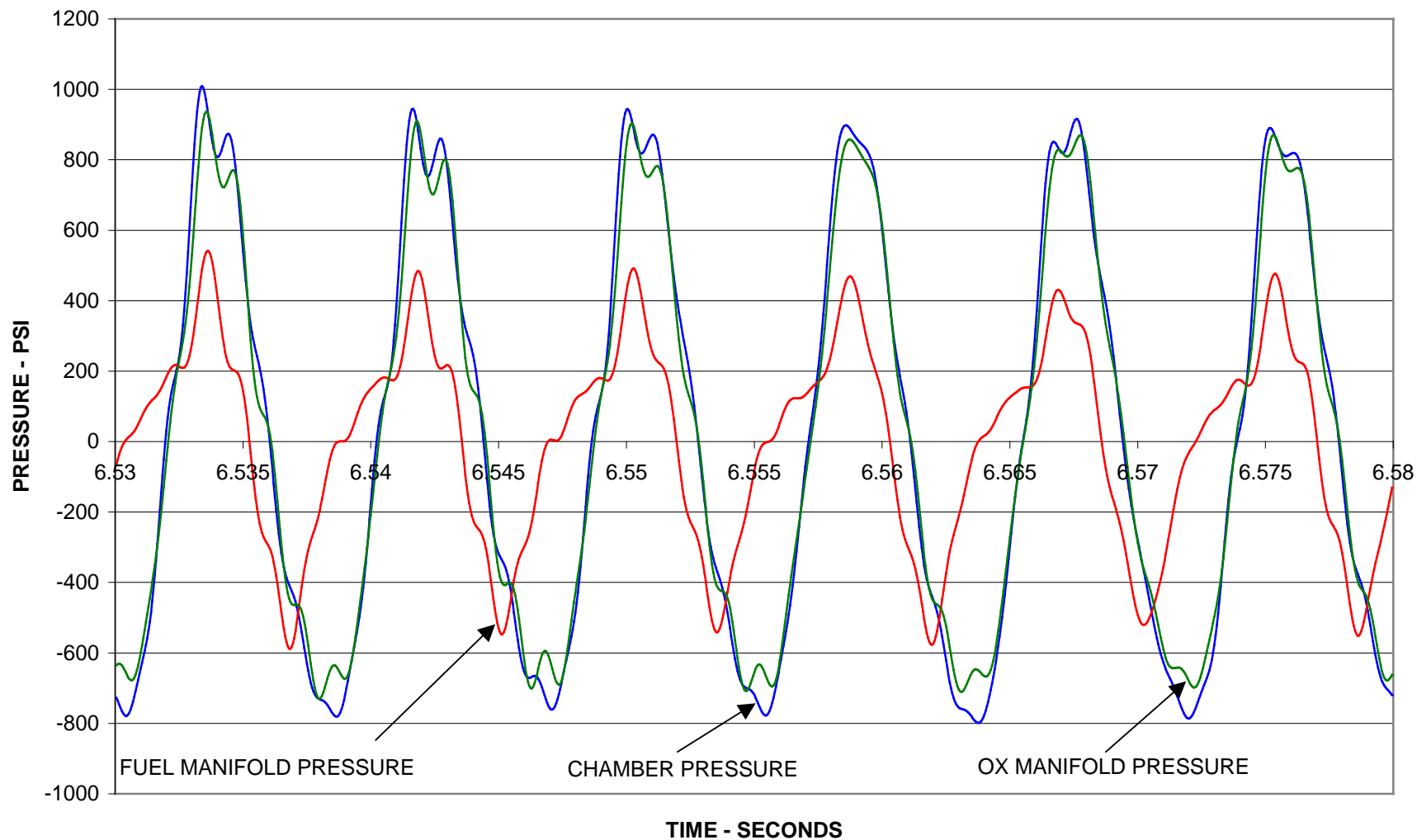
NASA TM X-948, December 1964.

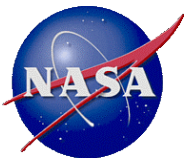




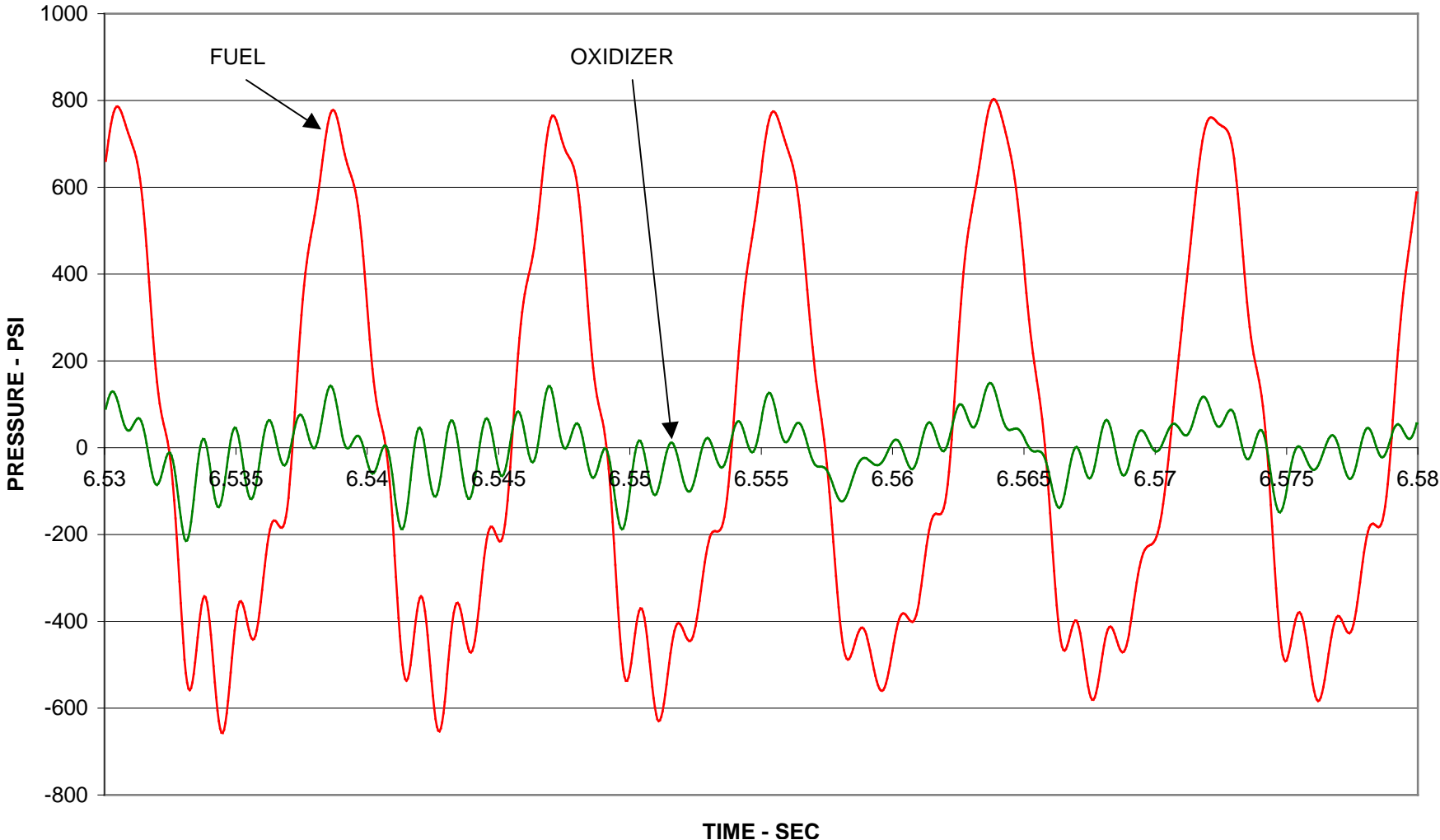
# Not So Nice Chug

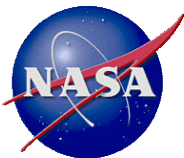
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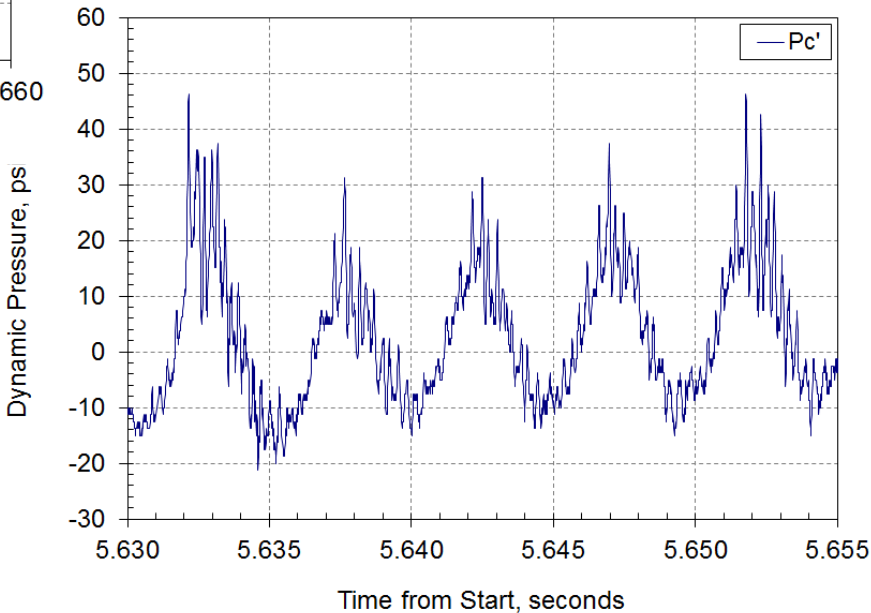
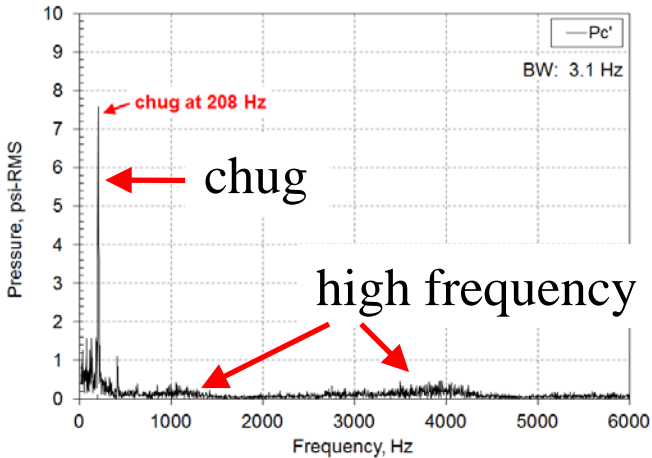
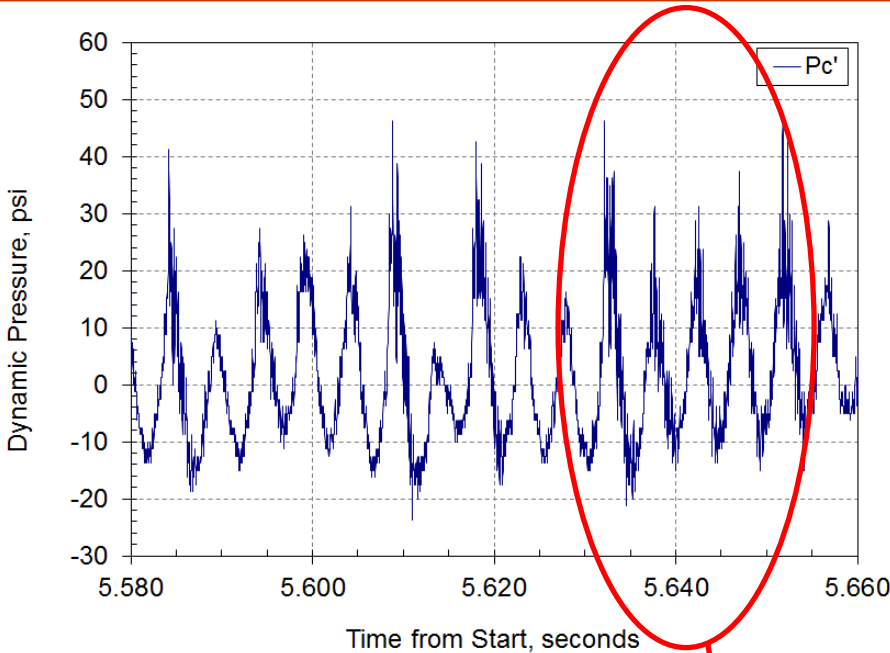


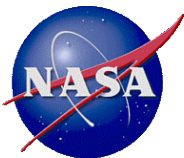
# Not So Nice Chug





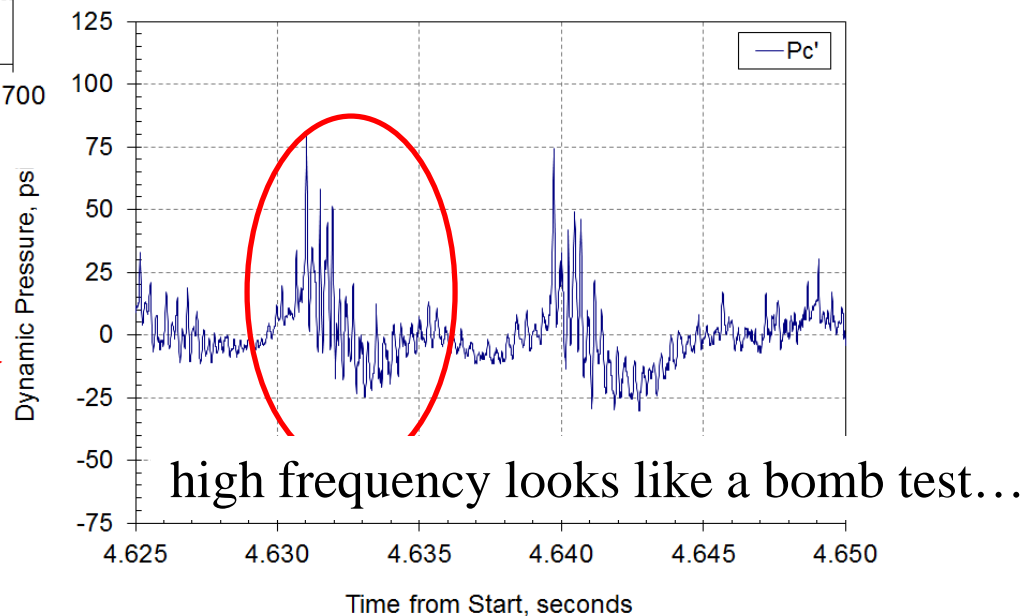
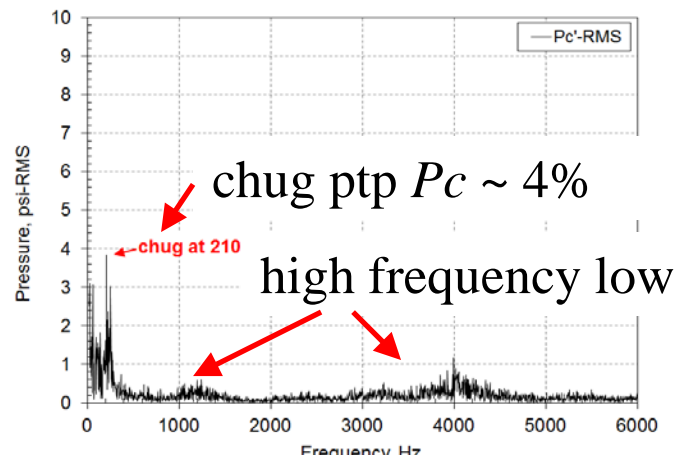
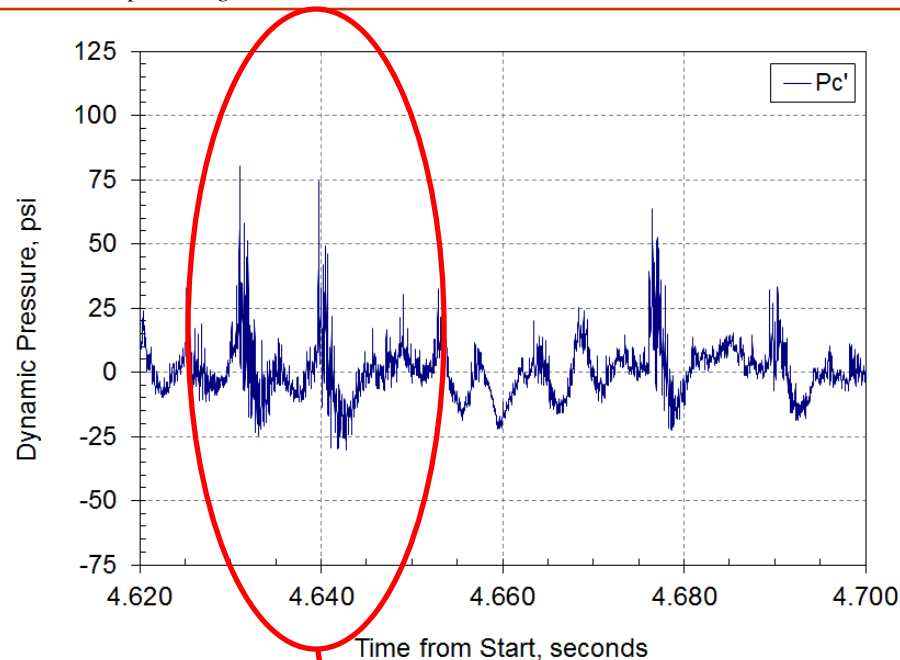
# Bad Chug

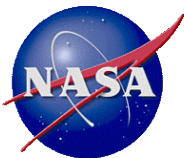




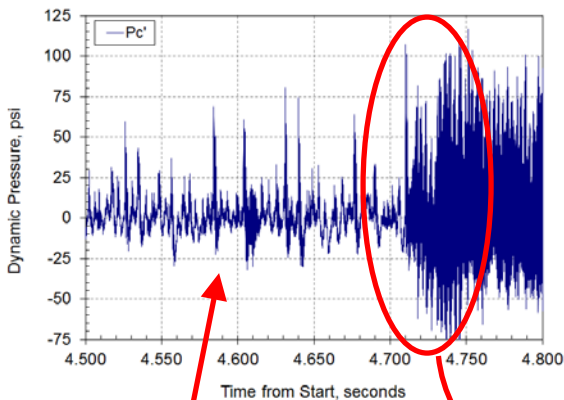
# Really Bad Chug

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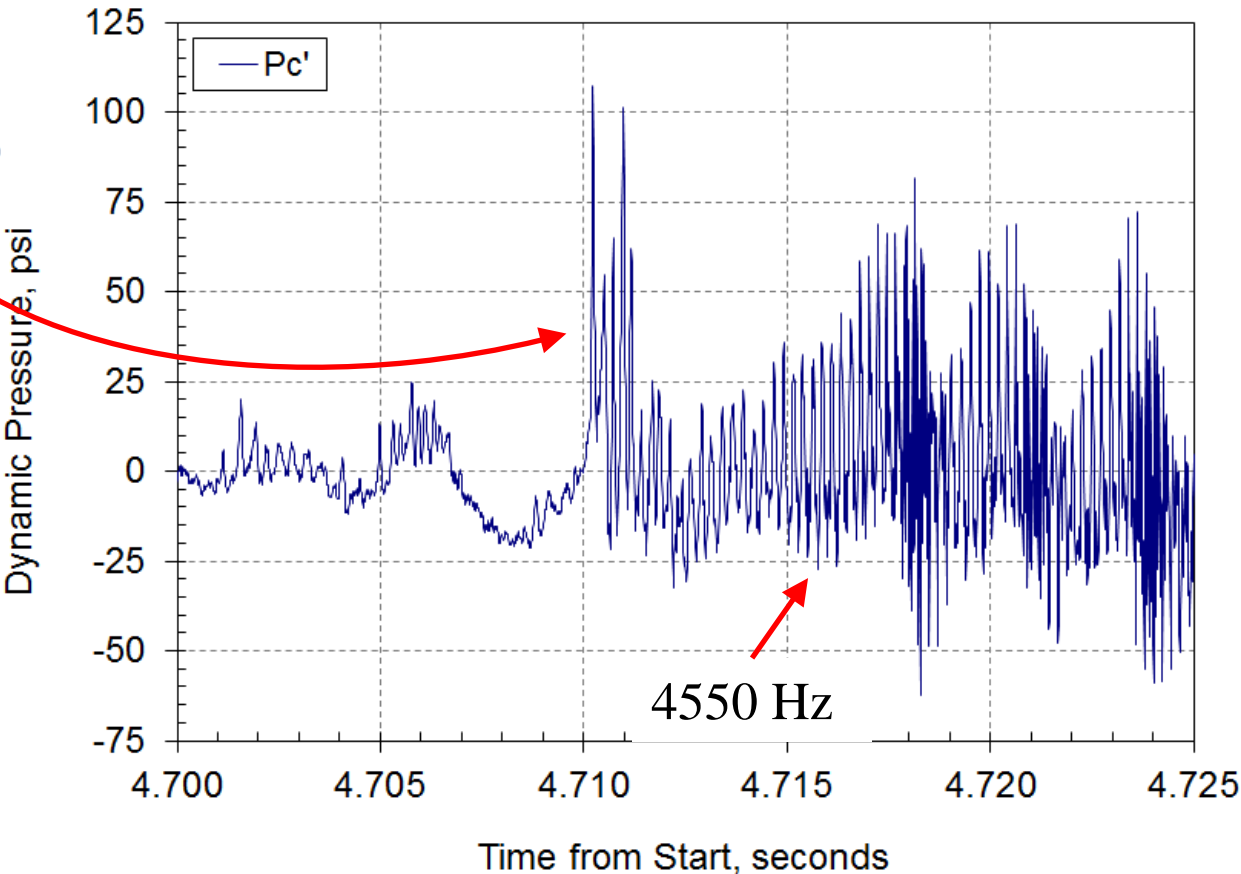


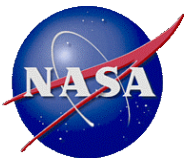


# Really Bad Chug



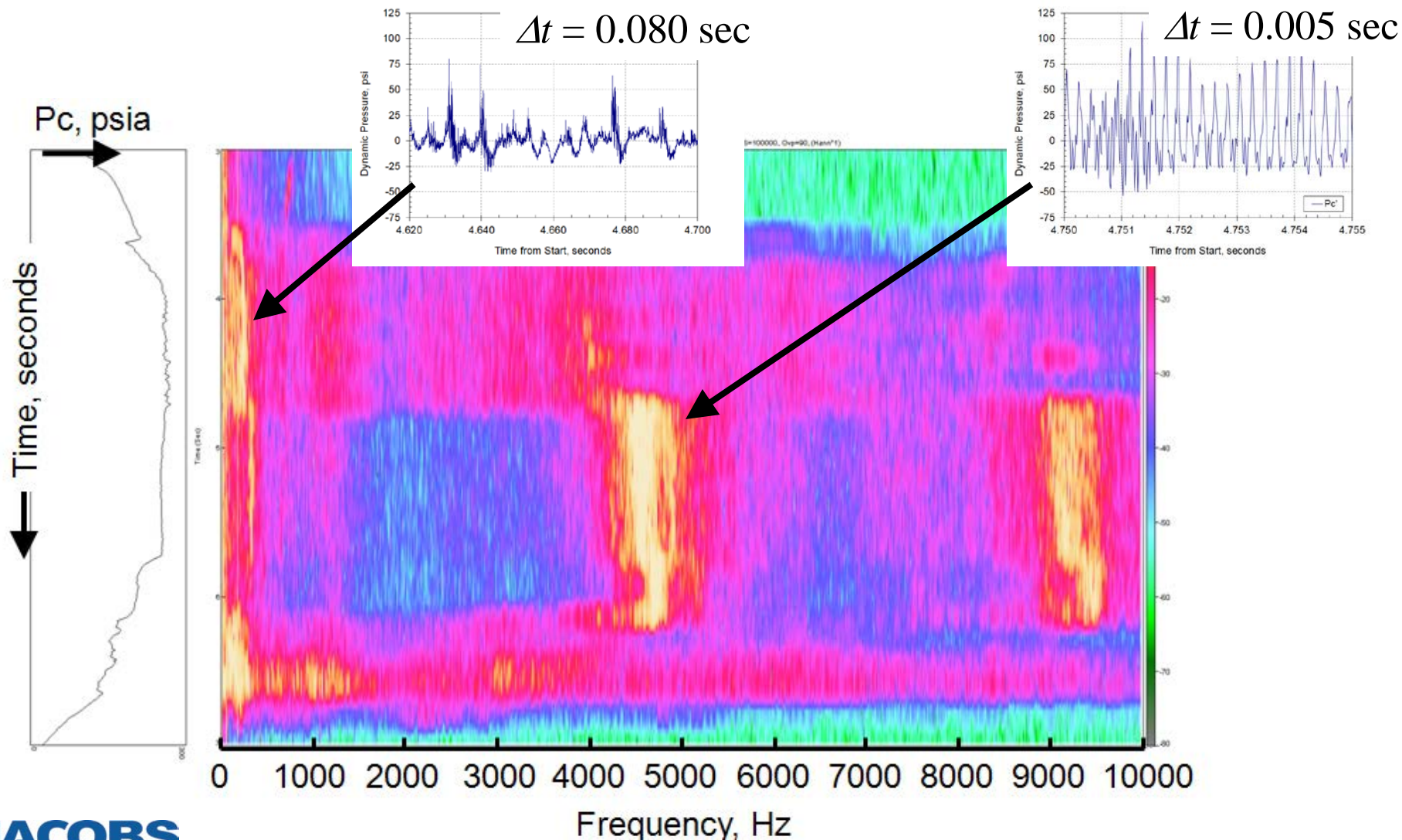
chug at 210 Hz

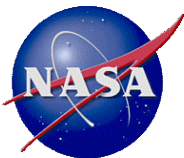




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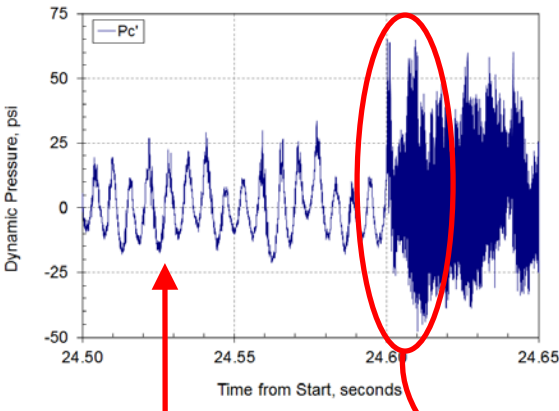
# Really Bad Chug



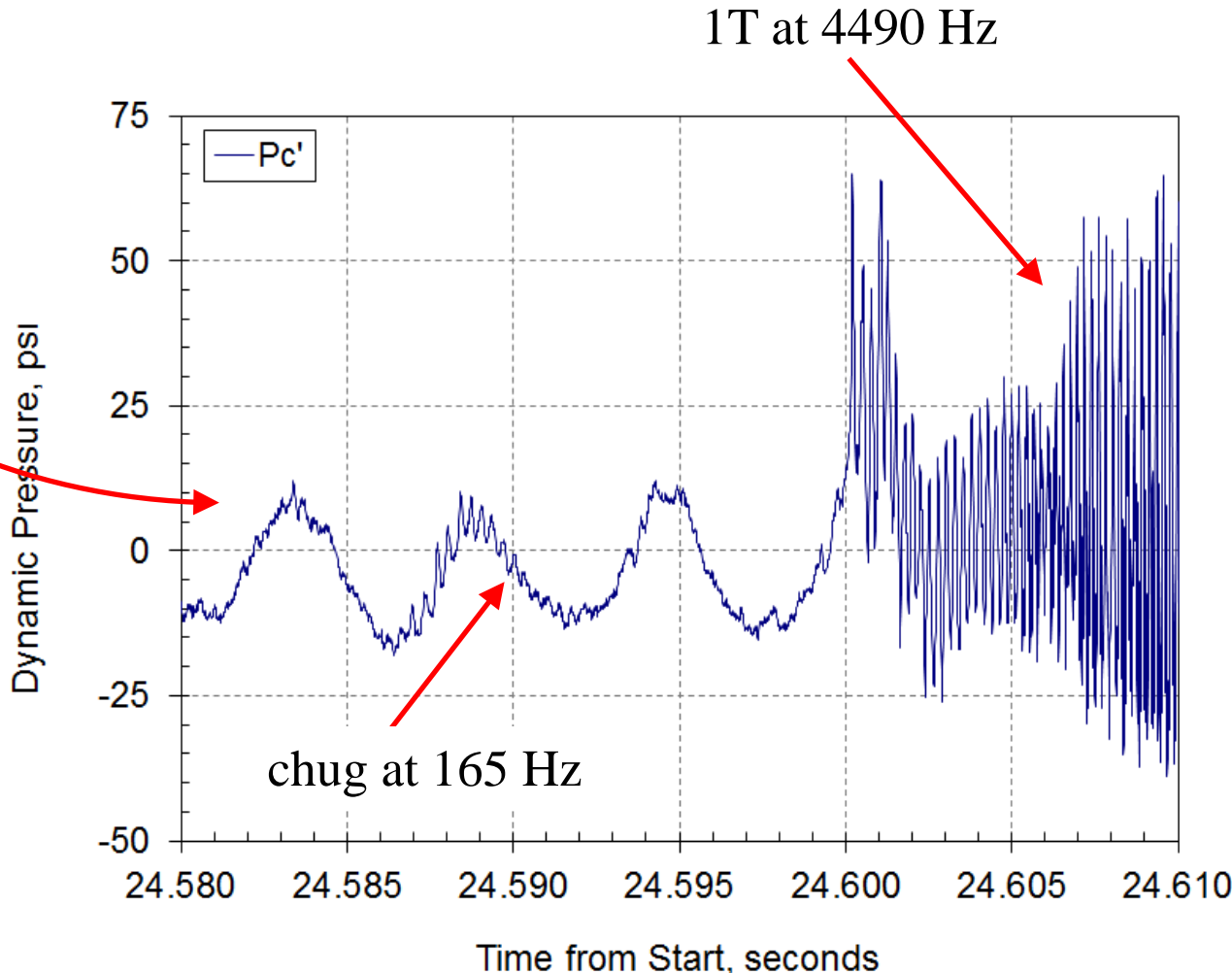


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# More Really Bad Chug



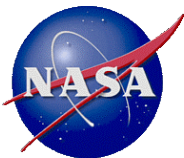
chug at 165 Hz



1T at 4490 Hz

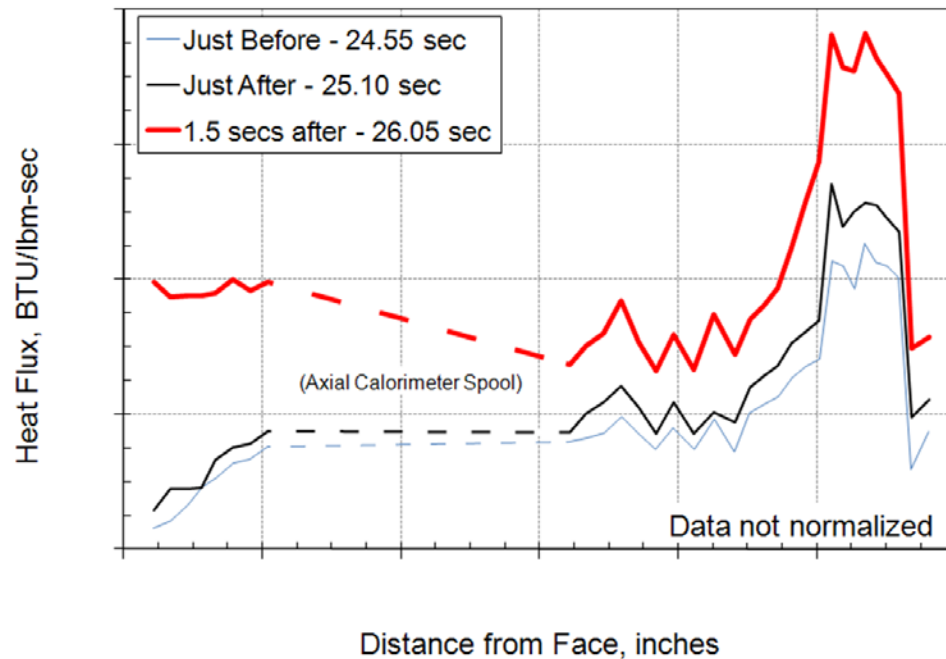
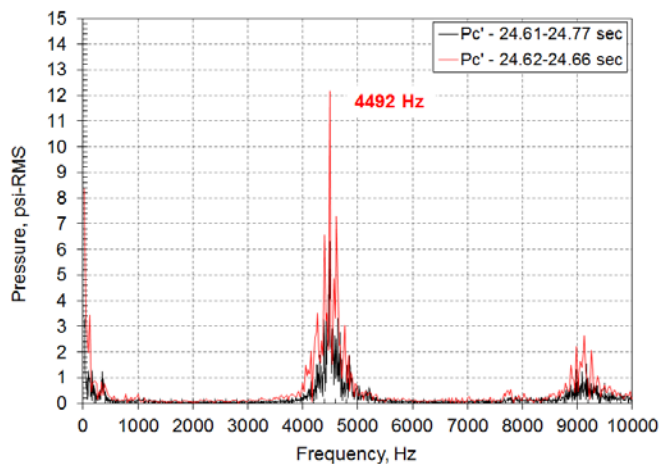
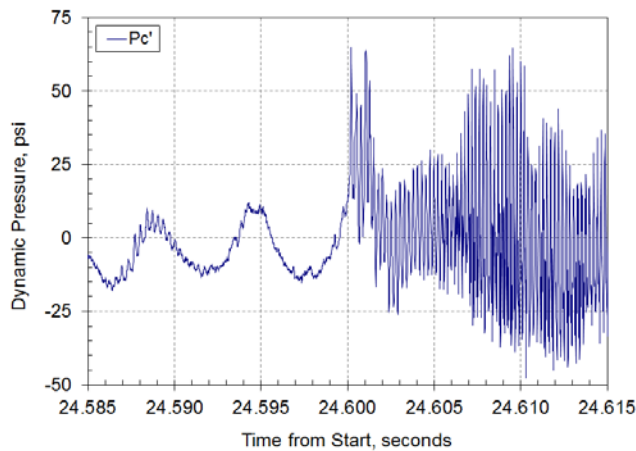
chug at 165 Hz





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# More Really Bad Chug



- 4490 Hz is 89% of equilibrium  $f_{1T}$
- Factor of 11 increase in head-end heat flux
- Factor of 1.8 increase in throat heat flux

...very likely the 1T mode





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# Really Really Bad Chug

Damage to injector  
element inserts





# Buzz

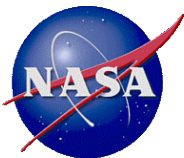
- An “intermediate frequency” combustion instability, displaying
  - wave motion in the combustion chamber although often not corresponding exactly to an acoustic mode
  - growing coherence from combustion noise, with slowly increasing amplitude
  - sometimes wave motion in the injector manifold or feed systems
- Often misunderstood and misdiagnosed
- Two different types have been observed based on the driving source
  - coaxial element oxidizer post “organ pipe” modes
    - often coupling to transverse acoustic modes
  - injector Helmholtz resonance mode
    - coupling to longitudinal acoustic modes



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# “Buzz” Associated with “Organ-Pipe” Resonances of the Coaxial Oxidizer Tube

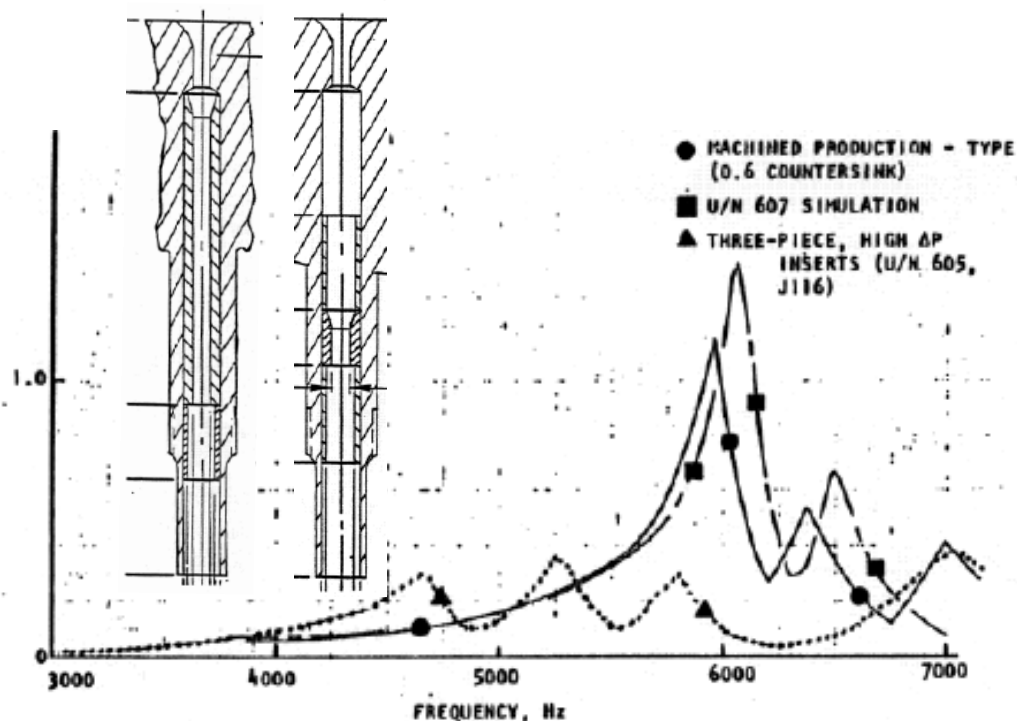
- Instability in J-2S engine development
  - interacting with dynamics of the element “recess” region
  - lightly coupled to 3T chamber acoustic mode
- Instability in late 1980s  $\text{LO}_2/\text{gCH}_4$  test program
  - coupled to 1T chamber acoustic mode



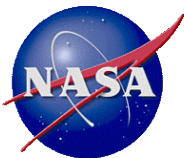
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# Complex “Organ Pipe” Buzz During J-2S Development

- Somewhat random oscillations, displaying characteristics of both acoustic instability and feed system-coupled instability
- Instability at 3T mode registered combustion chamber pressure oscillations ~150 psi-ptp, vibrations ~70 to 1000 g-RMS
- Modeling showed influence of oxidizer post, element recess, and chamber modes
- Resolved by inserts into posts

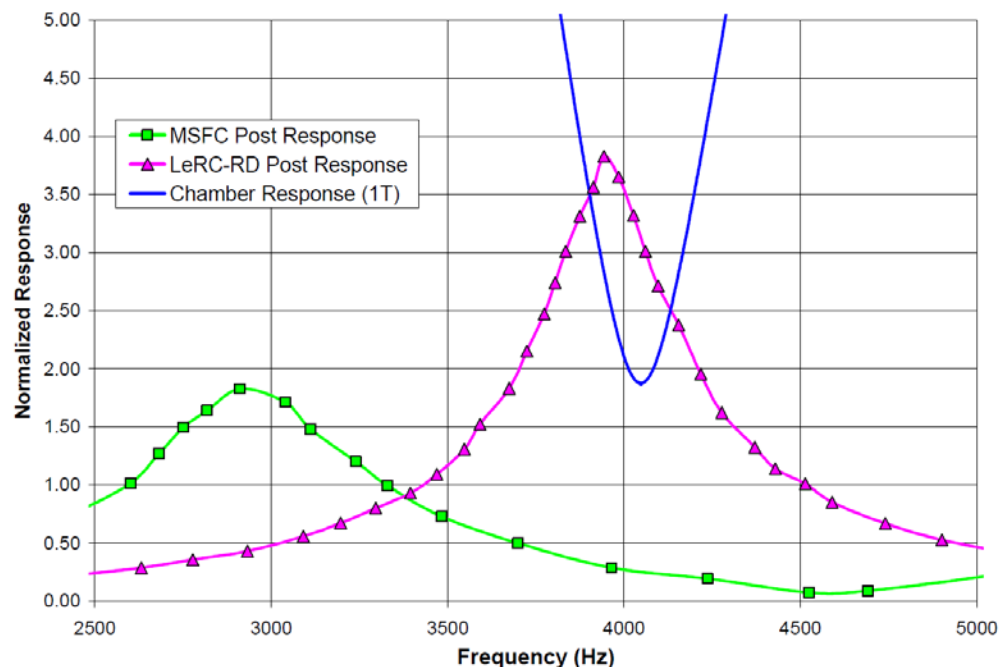


- See:
  - Anon., “4400-Hz Vibration Investigation, Final Report,” Rocketdyne Report R-8742, Contract NAS8-25156, Canoga Park, CA, June 30, 1971.
  - Hutt, J.J., and Rocker, M., “High-Frequency Injection-Coupled Combustion Instability,” Chapter 12, Liquid Rocket Engine Combustion Instability, V. Yang and W. Anderson, editors, Progress in Astronautics and Aeronautics, Volume 169, 1995, pp. 345-355.

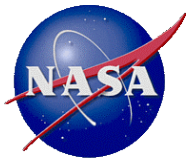


# “Organ Pipe” Buzz in Late 1980s

- Instability at 1T mode registered combustion chamber pressure oscillations ~300 psi-RMS, injector vibrations ~70 to 200 g-RMS
- $\text{LO}_2/\text{gCH}_4$  testing had otherwise been stable
- Modeling showed influence of organ pipe mode between two designs, one stable, one unstable



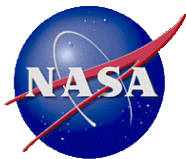
- See:
  - Jensen, R.J., Dodson, H.C., and Claflin, S.E., “LOX/Hydrocarbon Combustion Instability Investigation,” NASA CR-182249, Rocketdyne Report RI/RD 89-179, Contract NAS3-24612, July 1989.
  - Aithal, S.M., Liu, Z., Jensen, R.J., Hinerman, T.D., and Lynch, E.D., “Nonlinear Injection Transfer Function Simulations for Liquid Propellants,” AIAA Paper No. 2008-4742, July 2008.



# Another Form of “Buzz” Combustion Instability

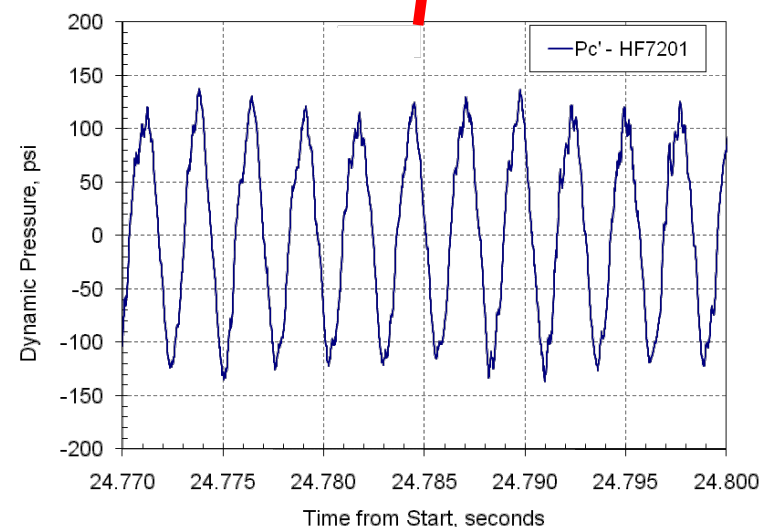
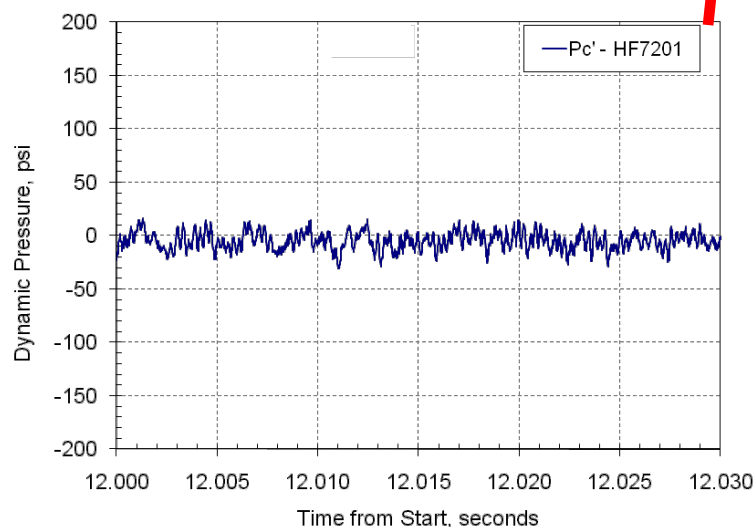
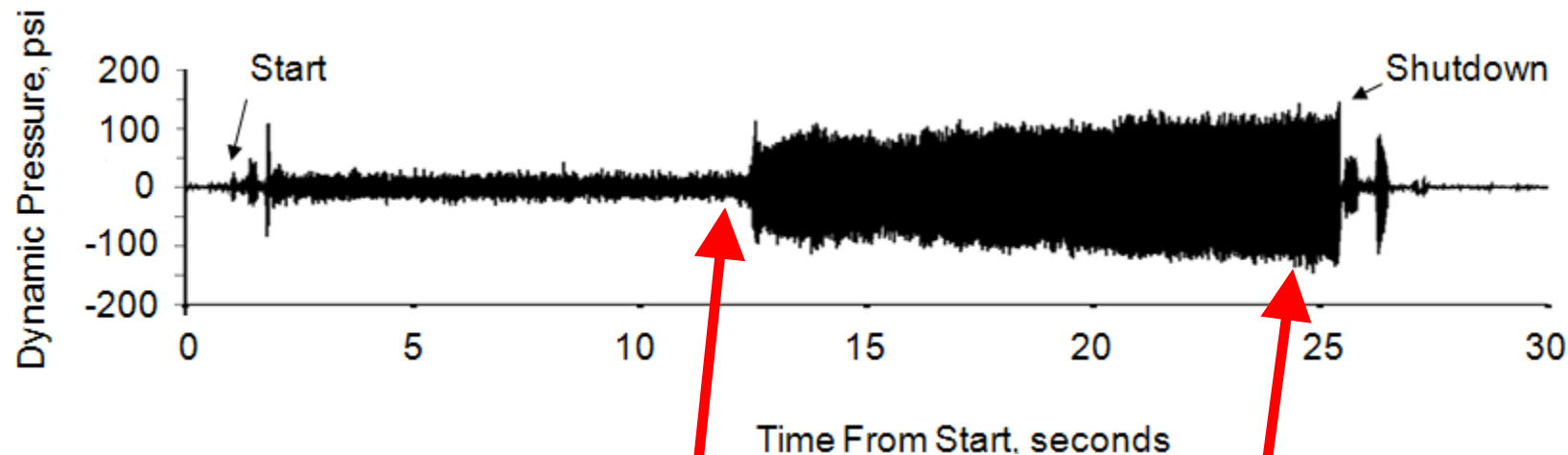
- Another type apparently provided issues for some older engines
  - Apollo Service Propulsion Module SPS engine
  - Shuttle Orbital Maneuvering System OMS
- This type has come back in many recent test programs
  - Gas generating combustion devices situated in long combustion chambers/ducts
  - Lots of arguments about what it was or wasn't
  - ... but it definitely was combustion instability
- Injector Helmholtz resonance mode coupled to longitudinal chamber acoustic modes

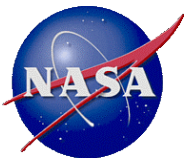




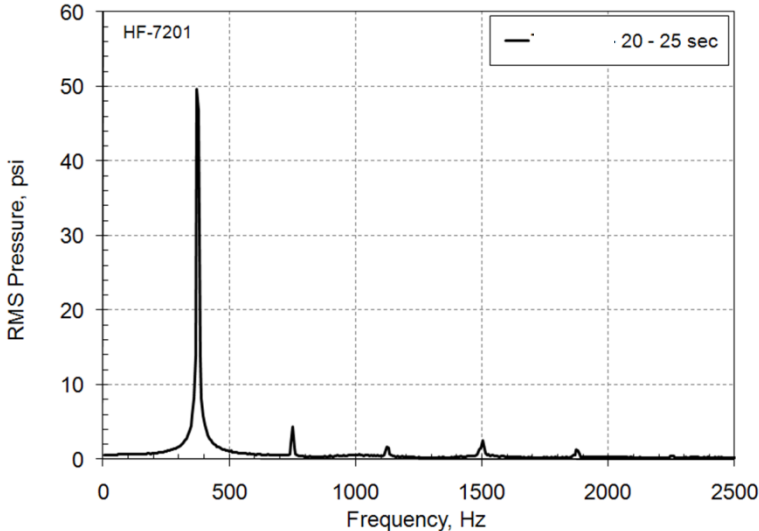
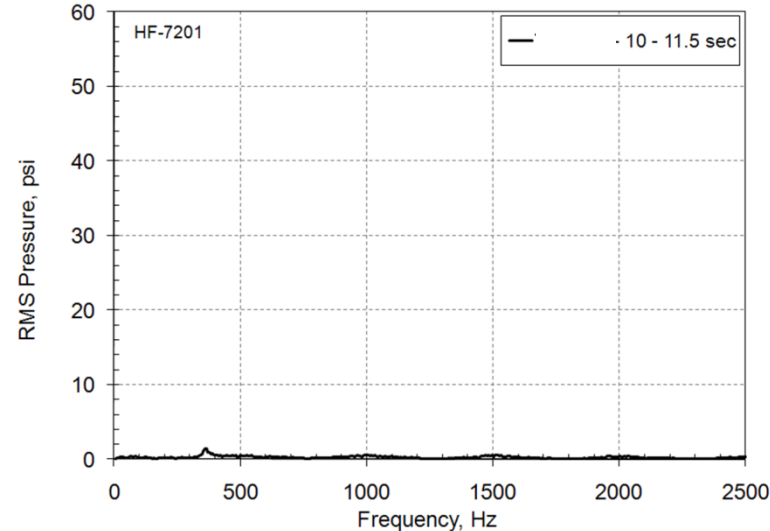
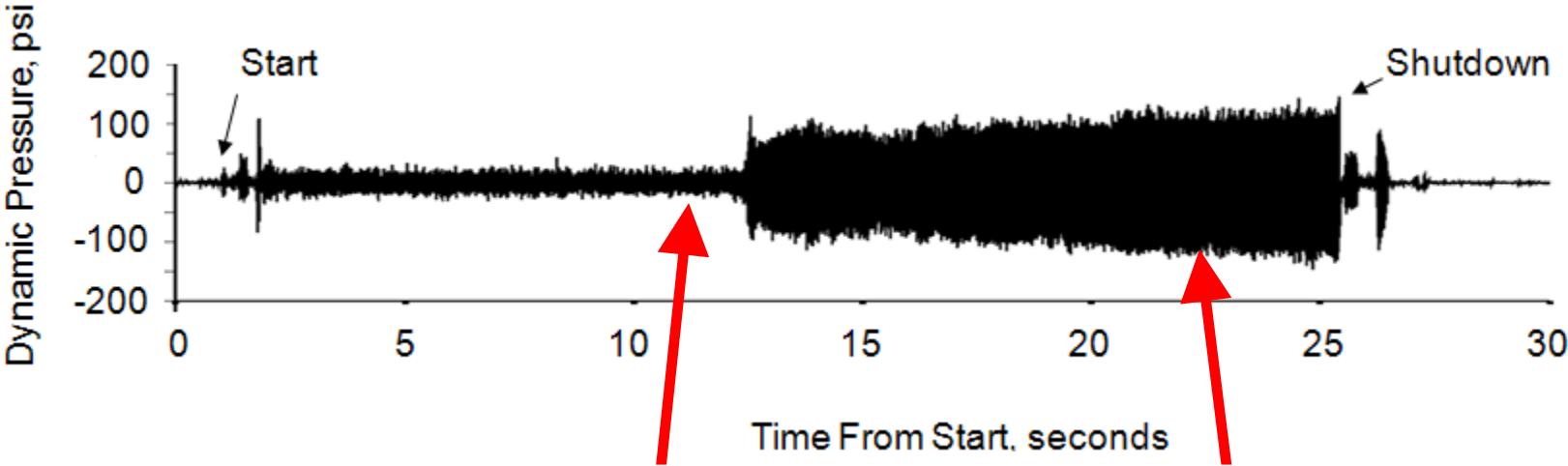
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# Combustion Instability Near 1L Acoustic Chamber Mode Appeared “Suddenly”

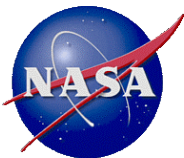




# Very Discrete

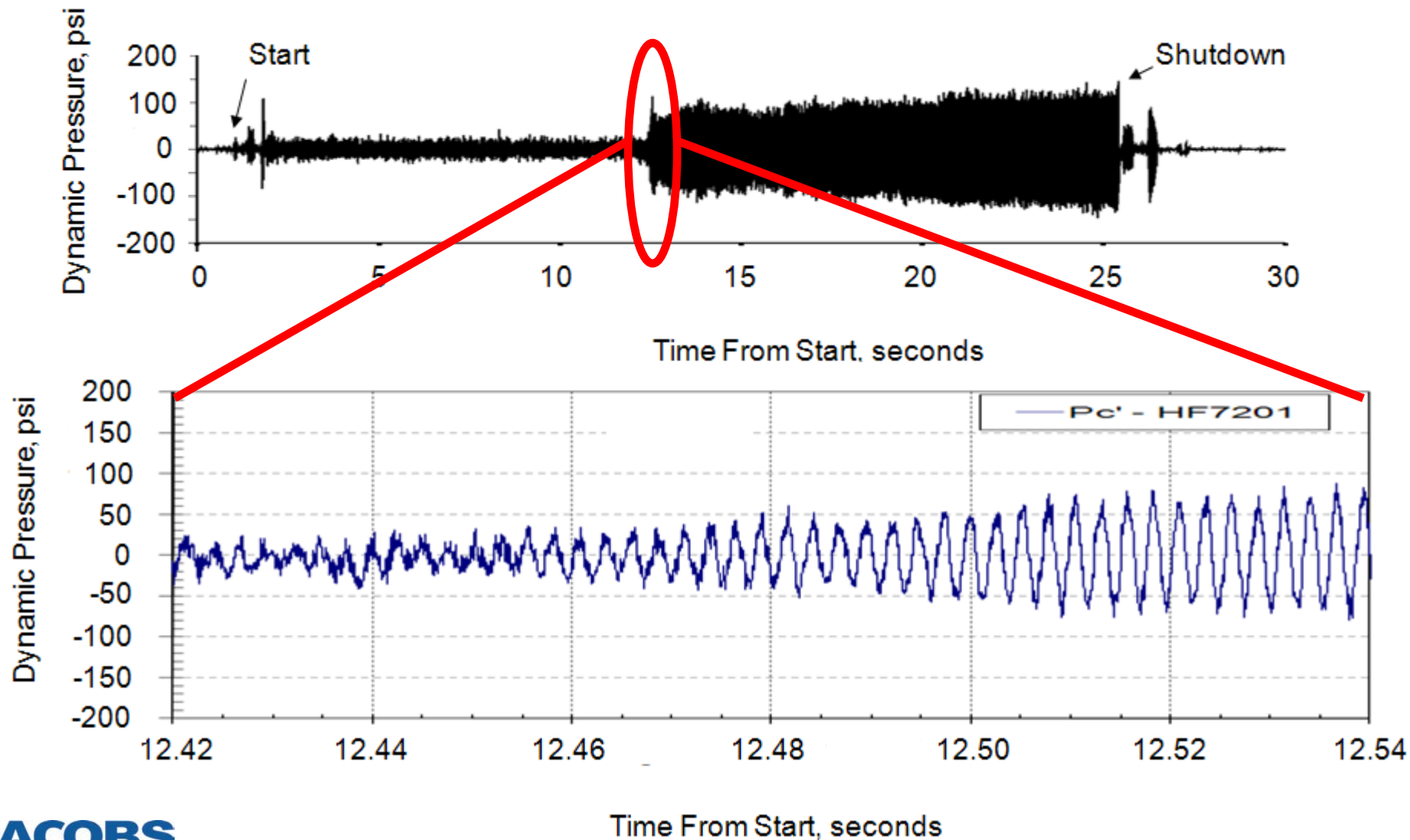


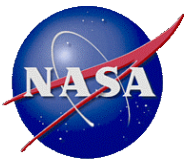




# Slow Growth During Transition to Instability

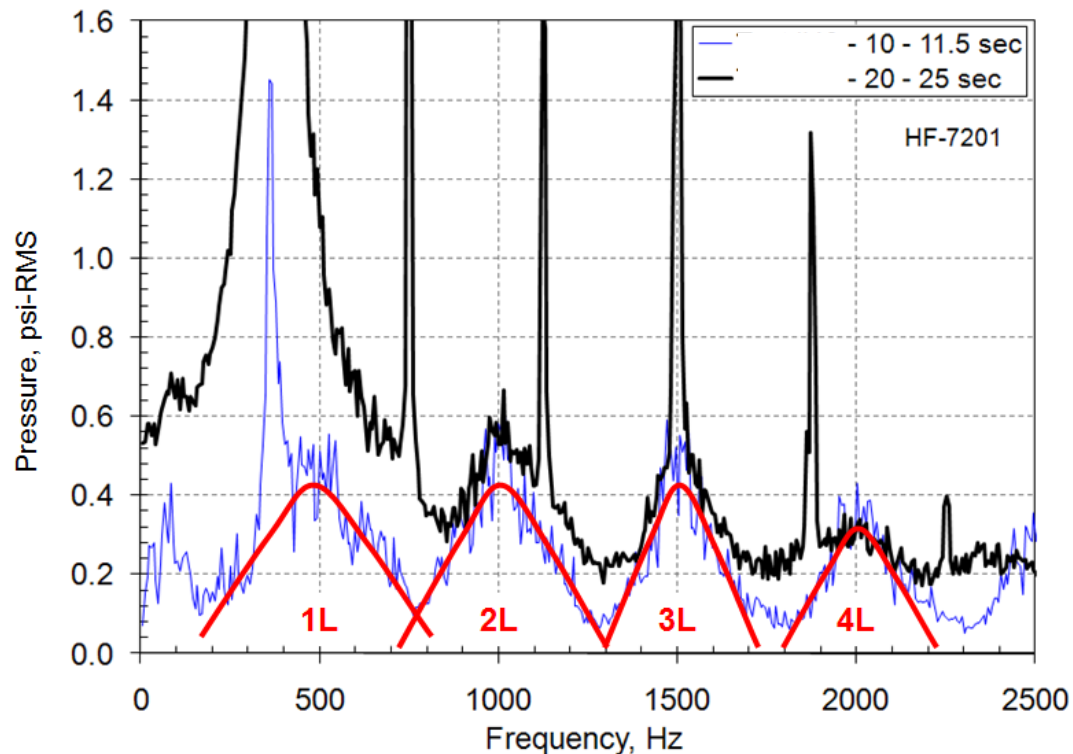
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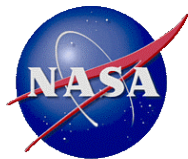




# Instability of the 1L Mode but Not Exactly *at* the 1L Mode

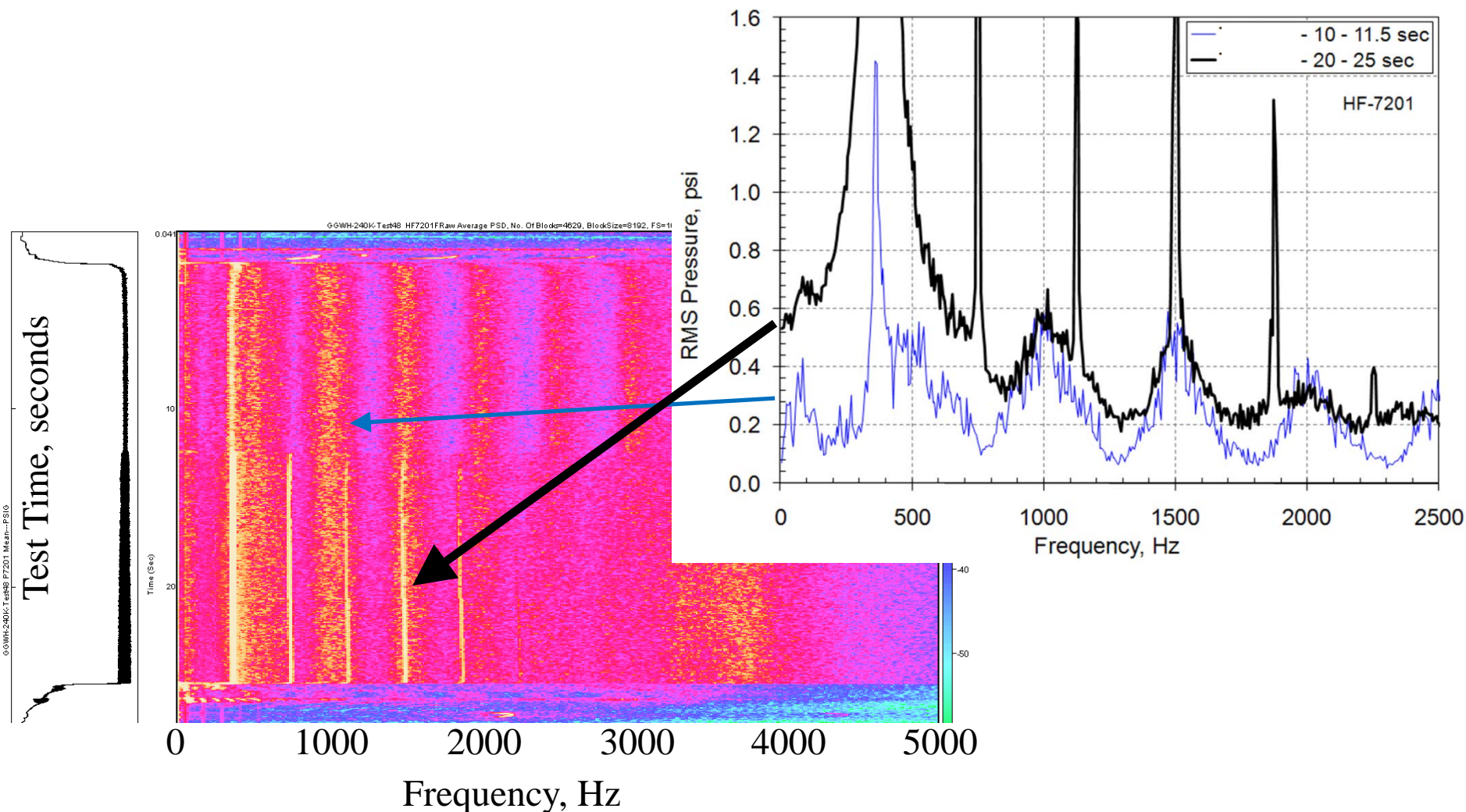
- Unstable at 378 Hz
- 1L mode frequency
  - early in test observe  $f_{1L} \sim 500$  Hz
  - observe higher order modes are same later in test
  - All chamber modeling suggests  $f_{1L} \sim 500$  Hz

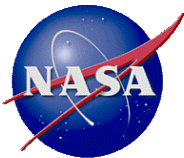




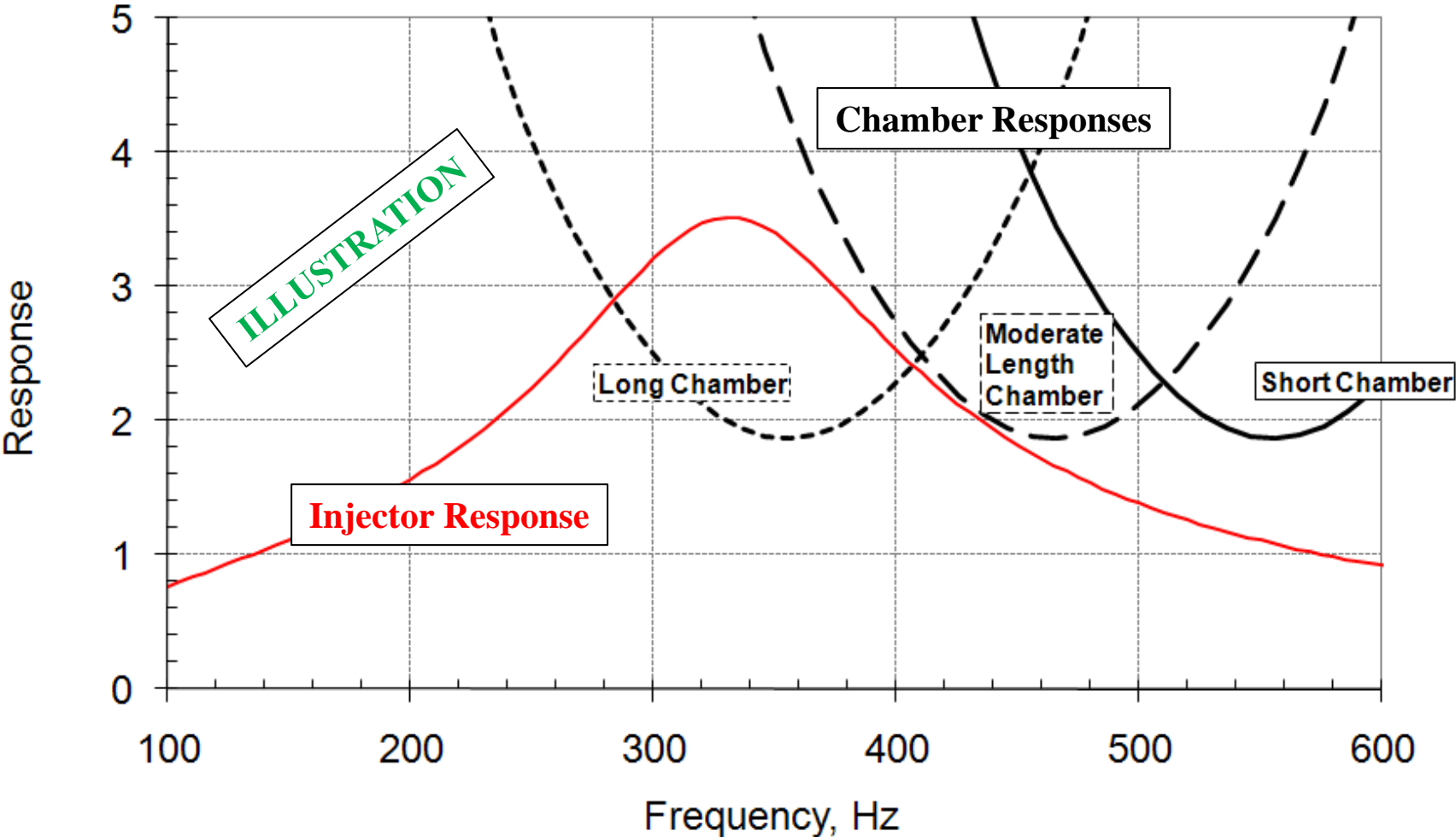
# Frequency of Instability was Present Early in Test Prior to “Instability”

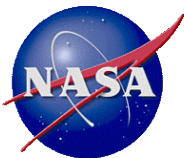
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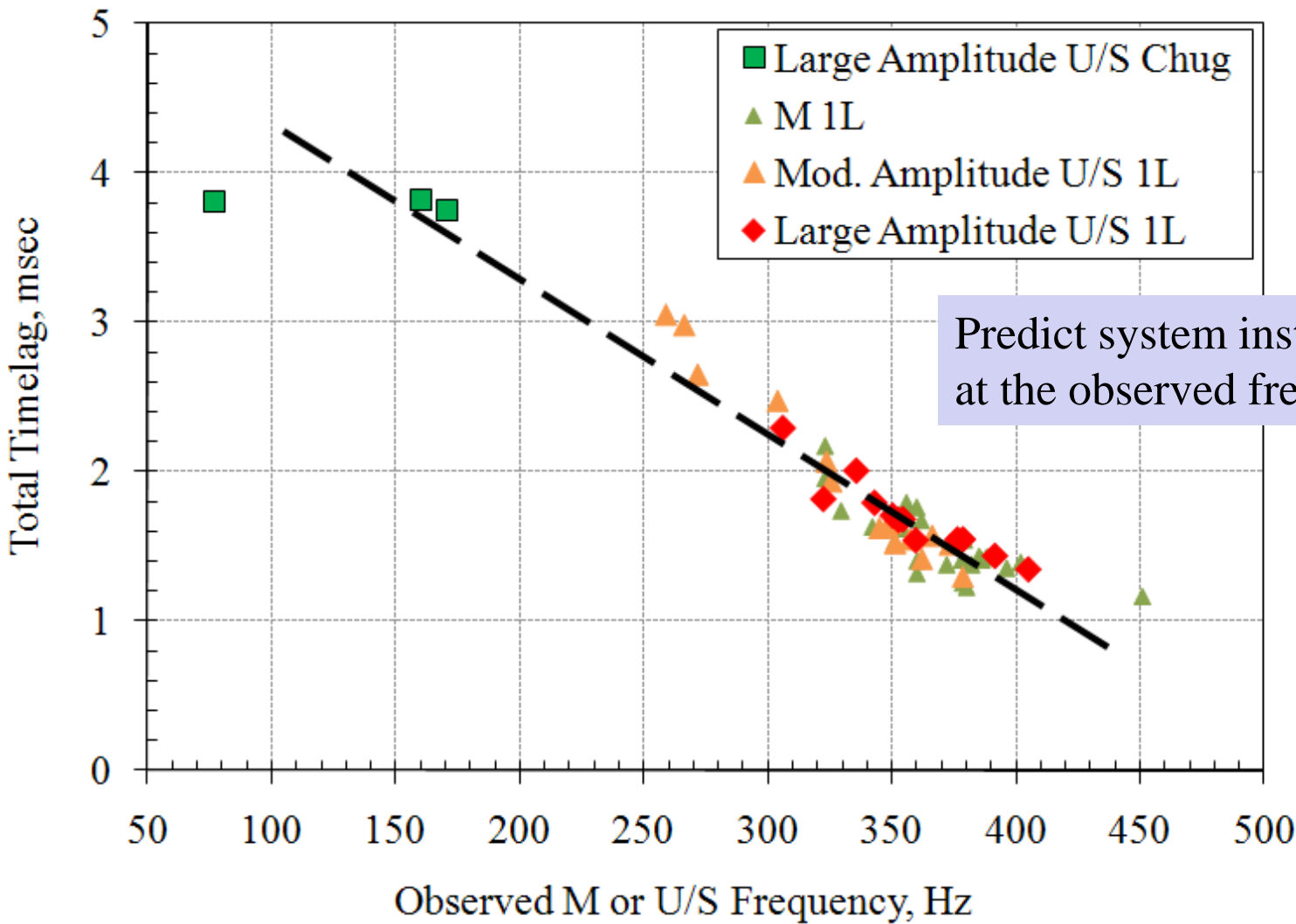


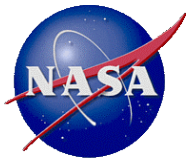
# General Transfer Function Analytical Formulation





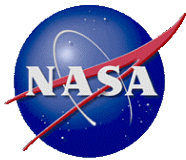
# Total Timelag Problem





# Summary

- Chug happens...
  - On almost every program... on almost every start or shutdown transient.
  - Vibration levels can be bad. Things get broken.
  - Modeling is getting pretty good. Use it !
- Buzz is happening ... again ...
  - Coupling to transverse acoustic modes associated with coaxial element oxidizer post organ pipe modes
  - Coupling to longitudinal acoustic modes associated with injector Helmholtz mode
  - Vibration levels can be bad. Things get broken.
  - Modeling capability isn't bad... but still needs work...
  - Some people still need convincing



# Motivating Comments from Years of Doing This

- Compile your design and test data for every program you work on
  - Keep at it throughout your career
  - Data are your blood – don't let your data get away from you
- Use your compiled data for continued analytical and empirical investigations
  - Don't let unanswered questions stay unanswered
  - Determine not only what happened, but why
- *The few that are unstable are more useful than the many that are stable*
  - Thanks Ross!





# Final

- Keep aware.... don't let this happen to you





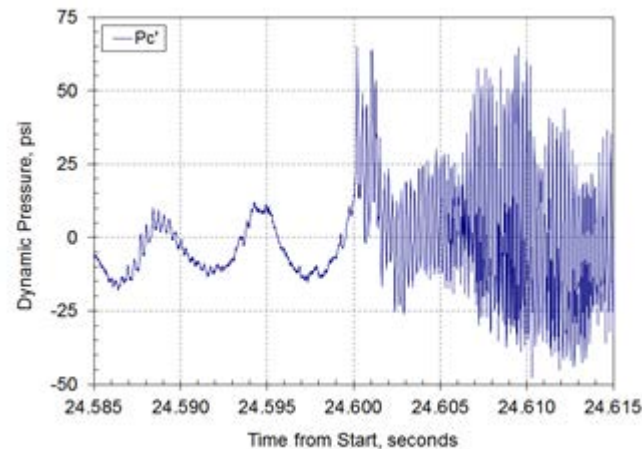
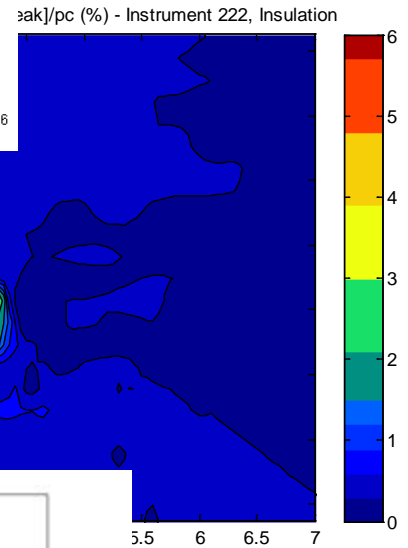
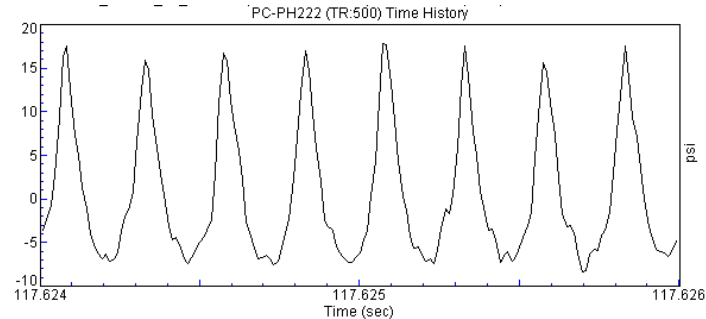
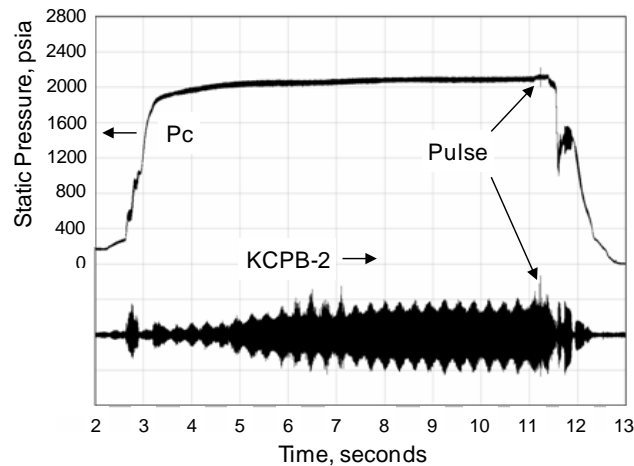


# Backup



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# The Problem: Dynamics Happens (and we don't always know why)





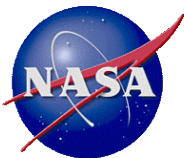
# Reasons for Occurrence of Combustion Instability

- Large combustion chamber diameters
- Long chamber lengths
- Insufficient injector pressure drops
- Fluid dynamic conditions inside combustion chamber susceptible to oscillations
  - Atomization, vaporization, mixing, reaction
- Injector geometrical features create potential for oscillations
- Propellant combination is capable of producing “pops”
- Start transient produces different transient temperatures, pressures, and flow rates that could create a “pop”



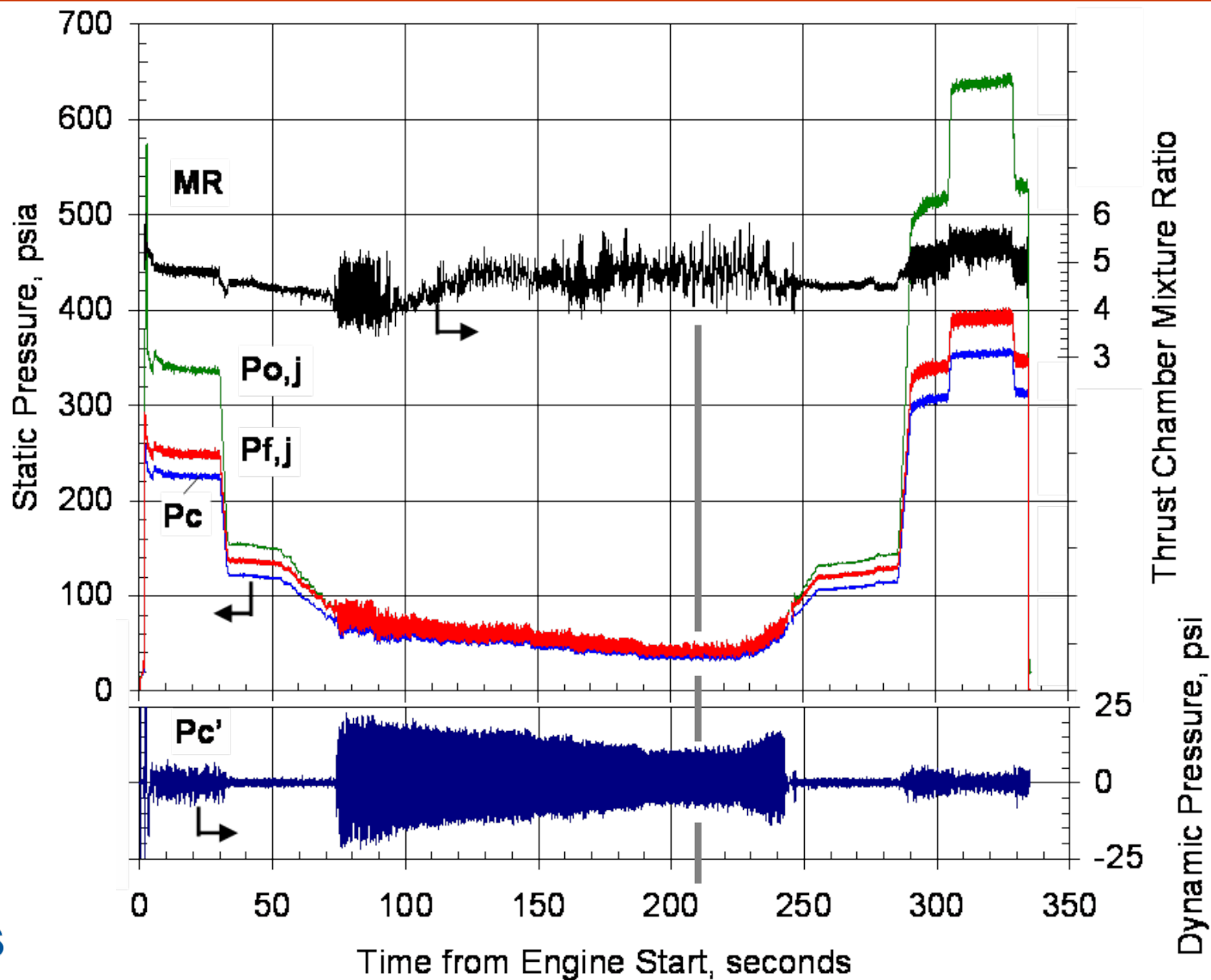
# Reasons for Occurrence of Combustion Instability, continued

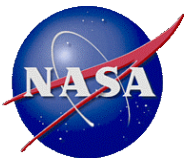
- Development program did not include sufficient testing to understand margins
  - i.e., you did not do enough to find out what your margins are
- Operating with insufficient margin after development
  - i.e., you know where the margins are and you operate too close to them
- Propellant combination is capable of producing “pops”
- Start transient produces different transient temperatures, pressures, and flow rates than examined during development program
- Change in manufacturing processes (even if dimensional characteristics are not changed)



# MR Excursions with Chug

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# More Bad Chug

